Interplay of static loads and subduction dynamics in foreland basins: Reciprocal stratigraphies and the “missing” peripheral bulge

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ABSTRACT

Foreland basins are created by superimposed mechanisms that flex the lithosphere. In addition to static loads, dynamic loading below the basin by viscous mantle corner flow above a subducting plate may cause long-wavelength subsidence. It is proposed that the interaction of the static and dynamic forces is responsible for the formation and preservation of recently recognized “reciprocal stratigraphies” in retro-foreland regions above subducting slabs. Reciprocal stratigraphies refer to a correlative succession of strata characterized by contrasting stacking patterns that reflect opposite base-level changes between proximal and distal settings. The same interactions may also modify the stratigraphy of the flexural peripheral bulge and mask its presence. An example from the Late Cretaceous of the Western Interior basin, Canada, illustrates the concepts.

INTRODUCTION

It is generally agreed (see DeCelles and Giles, 1996, for a review) that foreland basin systems form by the flexural warping of the lithosphere under a combination of supralithospheric and sublithospheric loads. Flexure of the lithosphere under concentrated static loads generates a downwarp proximal to the orogen, the foreland basin, and a low amplitude long-wavelength upwarp, the peripheral bulge or forebulge (Fig. 1). In addition to the static loads, there is increasing evidence that dynamic loading by viscous mantle corner flow coupled to the subducting slab may superimpose long-wavelength subsidence, particularly when there is rapid subduction of a shallowly dipping slab beneath the foreland basin (Mitrovica et al., 1989; Gurnis, 1992; Holt and Stern, 1994). When combined, these loading mechanisms lead to a conceptual model in which subduction dynamics and viscous corner flow can contribute to the formation of the flexural peripheral bulge and forebulge (Fig. 1). In the present context, reciprocal stratigraphies are characterized by correlative proximal and distal successions of strata. The accommodation necessary to create these successions is the result of superimposition of dynamic and static forcing.

Normally, when orogenic or slab pull static loads increase, the peripheral bulge is raised and eroded. The superposition of a sufficiently long-wavelength dynamic subsidence can, however, offset the uplift of the bulge and lead to sedimentation on the peripheral bulge as well as within the foreland basin. Under these circumstances the erosional characteristics of the bulge are suppressed and “missing” from the stratigraphic record, and the bulge may be unrecognizable. We suggest that this same superposition creates a new stratigraphic package, which has recently been recognized and termed reciprocal stratigraphies (Catuneanu et al., 1997). In the present context, reciprocal stratigraphies are characterized by correlative proximal transgressive and distal regressive strata and the converse situation. The accommodation for the reciprocal strata is created by the combined dynamic and static subsidence. The reciprocal properties of the strata reflect the differential subsidence and uplift of the foreland basin and peripheral bulge within the overall long-wavelength dynamic subsidence. The latter provides the accommodation necessary to create and preserve the reciprocal strata. If correct, our interpretation indicates that reciprocal stratigraphy is a diagnostic tool by which static and dynamic loading may be recognized and separated.

We interpret the absence of a recognized peripheral bulge in the Canadian part of the Late Cretaceous–early Cenozoic Western Interior (foreland) basin to be a consequence of superimposed moderate-wavelength static flexure and long-wavelength dynamic subsidence. This inference is consistent with the reciprocal architecture of the Bearpaw and Cannonball cycles from this region.

RECI PROCAL STRATIGRAPHY AND HINGE LINE POSITIONS FROM THE WESTERN INTERIOR BASIN

Examples of reciprocal correlation between proximal and distal sequences in a retro-foreland basin are offered by the Bearpaw (late Campanian–Maastrichtian, ca. 77–65 Ma) and Cannonball (Paleocene, ca. 65–55 Ma) cyclothems in the Western Canada basin (the Canadian portion of the Western Interior basin). These cyclothems include coeval marine and nonmarine facies separated by diachronous boundaries reflecting the time-transgressive character of both overall incursions and retreats of the interior seaways.

Figure 1. Static and dynamic loads that act on an orogen-foreland basin system. Pro- and retro- refer to the subducting and overriding lithospheres. Static loads act at the surface (the orogen, foreland fold and thrust belt, sediment and water) and beneath the system (e.g., slab pull). The subducting pro-lithosphere induces a dominant viscous corner flow (dashed lines) beneath the retro-lithosphere, which dynamically reduces the pressure and leads to subsidence (vertical arrows) of the retro-lithosphere that is greatest adjacent to the subduction zone. This dynamical loading depends on the viscous drag force and is proportional to the viscosity of mantle involved in the corner flow and the speed of subduction. The horizontal scale of the subsidence (Lg in text) is maximized when the slab dip is small.
The marine transgressive-regressive cycles of the Bearpaw strata have been studied through facies analysis at the regional scale of the Western Canada basin (Catuneanu et al., 1997). The analysis included outcrop and core sedimentology of reference sections, gamma ray and sonic log correlations along subsurface profiles (Fig. 2; Catuneanu, 1996), biostratigraphic (particularly ammonite) correlations (using the Caldwell et al., 1993 synthesis), and the use of bentonite beds for correlation and chronostratigraphy. As suggested by the lateral shift between open shelf and shoreface facies, the fining-upward successions are identified as transgressive systems tracts, whereas the coarsening-upward successions are identified as regressive systems tracts. Two distinct types of transgressive-regressive sequences have been recognized within the basin: proximal-type sequences (closer to the orogenic belt) dominated by regressive systems tracts having a transgressive to regressive systems tract ratio of 1/3, and distal-type sequences dominated by transgressive systems tracts having a transgressive to regressive systems tract ratio of 3/1.

A reciprocal correlation between the proximal and distal stratigraphies has been documented (Catuneanu et al., 1997): Proximal transgressive systems tracts and distal regressive systems tracts (as well as proximal regressive systems tracts and distal transgressive systems tracts) can be mapped as continuous, genetically related and correlative packages of strata with comparable thicknesses (Fig. 3). These results, anticipated in theoretical computer models (Jordan and Flemings, 1991), are supported by extensive bentonite seams that demonstrate that the correlative transgressive and regressive strata are of the same age (Fig. 3). The proximal to distal facies change takes place over an area a few kilometers wide that can be defined as a hinge zone. The mid-point of the hinge zone may be taken as the stratigraphic hinge line (distance $h_D$ from the orogen, Fig. 4).

Similar reciprocal stratigraphies between the proximal and distal sectors of the Western Canada basin have been established for the Maastrichtian-Paleocene nonmarine sequences, partially correlative with or overlying the Bearpaw marine facies (O. Catuneanu and A. R. Sweet, personal commun.). In addition, the interpretation of the coeval transgressive and regressive shorelines indicated by Gill and Cobban (1973), in terms of reciprocal proximal to distal stratigraphies and flexural tectonics, allowed the mapping of the hinge line position on the United States side of the Western Interior basin for the entire Campanian-Maastrichtian interval (Catuneanu, 1996). As an average position for the Campanian-Paleocene interval, the hinge line traces a semieliptical pattern outlining the region of maximum foreland basin subsidence (Fig. 2; Catuneanu, 1996).

**CONCEPTUAL INTERPRETATION OF RECIPROCAL STRATIGRAPHIES**

We interpret the synchronous reciprocal transgressive and regressive systems tracts, described previously, to imply simultaneous deepening and shallowing of the marine basin on either side of the hinge line. This behavior is attributed to a combination of static flexure of the lithosphere, which changes sign between the proximal foredeep and the distal peripheral bulge (Fig. 1; Beaumont et al., 1988; Jordan and Flemings, 1991) and long-wavelength dynamic subsidence.

Static loads ($L_S$, Fig. 4A) tend to be concentrated near the orogen and result in flexure with an exponentially decreasing magnitude. At some distance, $\lambda_S$, static deflections become negligible. A static hinge line (at distance $\lambda_{HS}$) can be defined where negative static deflections (basin subsidence) of a horizontal reference surface change to positive static deflections of much lower amplitude (peripheral bulge uplift), and the converse occurs when static loads decrease. The distance $\lambda_{HS}$ depends on the flexural properties of the lithosphere and the distribution of static loads.

Dynamic loads ($L_D$, Fig. 4A) are independent of static loads. They act on a length scale determined by mantle corner flow (Fig. 1) and cause tectonic subsidence of a horizontal reference surface over a distance $\lambda_D$. In many circumstances, particularly for small subduction dip, $\lambda_D > \lambda_{HS}$ (Mitrovica et al., 1989).

When static and dynamic loads combine to cause subsidence and $\lambda_D > \lambda_{HS}$, the tectonic deflection of the horizontal reference surface may look like the solid line (Fig. 4B). The adjacent dashed lines (Fig. 4B) show the conceptual change to the deflection when the static load is increased, $L_S(I)$, or decreased, $L_D(D)$, while $L_S$ remains constant. Correspondingly, the change in deflection when the dynamic load is increased, $L_D(I)$, or decreased, $L_D(D)$, while $L_S$ remains constant is shown by the dashed lines (Fig. 4C).

The sedimentary response can be complex. However, the general effect is the creation of reciprocal increases and decreases in accommodation space on either side of $\lambda_{HS}$ when $L_D$ is constant and $L_S$ varies. Corresponding reciprocal transgressive and regressive systems tracts will be created if sedimentation rates are smaller than the rate of change of accommodation space (Fig. 4B situation). This mechanism provides a simple explanation for the creation of reciprocal stratigraphies. An increase in $L_D$ provides an equally simple explanation for their preservation. The role of the long-wavelength dynamic load is twofold: to create accommodation space above the static peripheral bulge so that deposition, not erosion, will occur, and to cause additional subsidence necessary to preserve reciprocal sequences against later static uplift of the peripheral bulge. While $L_D$ remains constant, as assumed in Figure 4B, $\lambda_D = \lambda_{HS}$ and the hinge line position measures the normal static width of the foreland basin. The distal...
Figure 4. Conceptual effects of static ($L_S$) and dynamic ($L_D$) tectonic loads on retro-foreland basins and some sedimentary consequences. A: Tectonic deflection of horizontal reference surface by loads acting independently for case $L_D > L_S$. B: Combined deflection when $L_S$ and $L_D$ act together (solid line) and effect (dashed lines) of increases, $L_S$, and decreases, $L_S$, in static load while $L_D$ is constant. C: Sensitivity of same combined deflection (solid line, B) to increases, $L_D$, and decreases, $L_D$, in dynamic load while $L_S$ is constant (dashed lines). D and E: Topographic-bathymetric profiles illustrating likely stratigraphic response of basin to tectonics illustrated in B. Dynamic deflection has created marine accommodation across most of basin. D: Increased static load increases foredeep accommodation, reduces peripheral bulge accommodation, and leaves back-bulge accommodation unchanged. If sedimentation rates are less than rate of change of accommodation, proximal transgression (transgressive systems tracts) is coeval with peripheral bulge regression (regressive systems tracts). E: The converse of D.

SPECULATIONS REGARDING THE WESTERN INTERIOR BASIN AND CONDITIONS FAVORING THE CREATION OF RECURRENT STRATIGRAPHIES

On the largest scale, the eastward-dipping subducting plate beneath western North America has been interpreted to have had a time-varying subduction dip angle, largely based on sweeping magmatic patterns (Coney and Reynolds, 1977; Armstrong and Ward, 1991, 1993; Constenius, 1996) and varying subduction velocity (see Ward, 1995, for a review). If this interpretation is correct, the changes in dip angle should be recorded in the foreland basin stratigraphy as relative changes in the length scale, $\lambda_{DP}$, of dynamic loading. The magmatic patterns suggest that moderate to steeply dipping
subduction occurred during most of the Cretaceous period. Magmatism migrated eastward during latest Cretaceous to early Eocene time (ca. 75–54 Ma), extending to a maximum ~1000 km east of the trench. This migration is interpreted to result from a shallowing of the subduction dip. Early-middle Miocene magmatism rapidly migrated westward, interpreted as a return to a steep subduction dip angle.

What are the predicted consequences of such net changes in slab dip angle (steep-shallow-shallow) for the creation and preservation of reciprocal stratigraphies? On the basis of λD estimates from Mitrovica et al. (1989, Fig. 13), steep slabs (dip > 45°) have λD ≤ 500 km, so that λD ~ λHS for the Western Interior basin when the position of the supracrustal static loads east of the trench is taken into account. Under these circumstances, the width of a basin created by dynamic loads is similar to that of a basin created by static loads and the potential to distinguish these mechanisms on the basis of length scales is poor, particularly when the effects of other factors (e.g., sea-level fluctuations, loading history, sediment supply, local heterogeneities) are considered. The stratigraphy would most likely be interpreted as that resulting from simple static orogenic loading, but the load would be incorrectly estimated. One diagnostic feature is that a normal peripheral bulge should be recognizable when λD ≥ λHS. Shallow slabs (having dips of 30° or 20°) have λD ~ 1000 km or approaching 2000 km, respectively (Mitrovica et al. 1989, Fig. 13). Therefore, λD > λHS for the Western Interior basin, and the potential to distinguish dynamic and static effects on the basis of reciprocal stratigraphies increases. In addition, the net change in accommodation space following a slab dip decrease is mainly one of increased wavelength and can produce a distal stratigraphic signature that is similar to a first-order reciprocal stratigraphy. Therefore, the potential to distinguish dynamic and static effects on the basis of reciprocal stratigraphies increases. In addition, the net change in accommodation space following a slab dip decrease is mainly one of increased wavelength and can produce a distal stratigraphic signature that is similar to a first-order reciprocal stratigraphy.

The implications with respect to the Western Interior basins are as follows. (1) Creation of reciprocal stratigraphies is favored when λD > λHS (inferred to be approximately the 75–54 Ma interval) and peripheral bulges may be “missing” (i.e., unrecognized) for this interval. (2) When λD ≤ λHS, reciprocal stratigraphies are not favored (i.e., before ca. 75 Ma), but peripheral bulges are. (3) Preservation of reciprocal stratigraphies is favored when λD > λHS and λD increases (i.e., times of accelerating subduction, inferred to be the 75–55 Ma interval; see Ward [1995] for a review). These predictions are in accord with the observations. Moreover, it is unlikely that eustatic sea-level rise is the primary preserver of reciprocal stratigraphies in the Western Interior basin during latest Cretaceous and early Cenozoic time because the sediment thickness variation across the basin requires a persistent long-wavelength component in accommodation space (Mitrovica et al., 1989).

CONCLUSIONS

Reciprocal stratigraphies have recently been identified in the Bearpaw and Cannonball (77–55 Ma) cycles of the Canadian part of the Western Interior basin. Reciprocal stratigraphies consist of correlated proximal transgressive and distal regressive facies, and vice versa, and the interface separating them, termed the hinge line, can be mapped in space and time. Retro-foreland basins, including the Western Interior basin, are subject to static and dynamic (mantle corner flow) loads, amplitudes Ls and LD, which cause subsidence with respective wavelengths λHS and λD. The sedimentary response to these combined tectonic loads, when λD > λHS, is likely a cause of reciprocal stratigraphies. The most simple combinations are: Ls varies while LD is constant (which creates reciprocal stratigraphies and disguises the peripheral bulge), and LD increases while Ls is constant (which preserves these stratigraphies).

Our tectonic explanation of the Bearpaw and Cannonball reciprocal stratigraphies is consistent with the inferred shallow dip (λD > λHS) and acceleration (LD increasing) of the subducted plate beneath western North America at that time, ca. 75–55 Ma. If the proposed relationship between reciprocal stratigraphies and the tectonic model is confirmed, mapping such strata has the potential to identify and separate static and dynamic effects in foreland basin systems and to place constraints on paleo-subducting slabs.

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